

*RUNNING AND RESPONDING REINFORCED BY
THE OPPORTUNITY TO RUN:
EFFECT OF REINFORCER DURATION*

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The present study investigated the effect of reinforcer duration on running and on responding reinforced by the opportunity to run. Eleven male Wistar rats responded on levers for the opportunity to run in a running wheel. Opportunities to run were programmed to occur on a tandem fixed-ratio 1 variable-interval 30-s reinforcement schedule. Reinforcer duration varied across conditions from 30 to 120 s. As reinforcer duration increased, the rates of running and lever pressing declined, and latency to lever press increased. The increase in latency to respond was consistent with findings that unconditioned inhibitory aftereffects of reinforcement increase with reinforcer magnitude. The decrease in local lever-pressing rates, however, was inconsistent with the view that response strength increases with the duration of the reinforcer. Response rate varied inversely, not directly, with reinforcer duration. Furthermore, within-session data challenge satiation, fatigue, and response deprivation as determinants of the observed changes in running and responding. In sum, the results point to the need for further research with nonappetitive forms of reinforcement.

Key words: reinforcer duration, wheel running, lever press, rats

A response-strength conception of reinforcement (de Villiers & Herrnstein, 1976; Herrnstein, 1970) implies that as magnitude of reinforcement increases, the rate of the reinforced response should increase. However, the findings of numerous attempts to demonstrate this relationship using appetitive forms of reinforcement have been equivocal. Previous research into the relationship between reinforcer magnitude and overall response rates in free-operant paradigms using a variety of simple schedules (e.g., fixed interval, fixed ratio, variable ratio, variable interval) with various types of reinforcers (e.g., pellets, grain, sucrose solution) has yielded a confusing array of findings. Overall response rates varied directly (Harzem, Lowe, & Priddle-Higson, 1978; Hutt, 1954; Jenkins & Clayton, 1949; Meltzer & Brahlek, 1968, 1970; Reed & Wright, 1988; Stebbins, Mead, & Martin, 1959), inversely (Lowe, Davey, & Harzem, 1974; Priddle-Higson, Lowe, & Harzem, 1976; Staddon, 1970), in an inverted U-shape function (Conrad & Sidman, 1956; Guttman, 1953; Kliner, Lemaire, & Meisch, 1988), or showed no systematic relationship (Catania,

1963; Keesey & Kling, 1961; Powell, 1969) with reinforcer magnitude. In general, the effects of magnitude of the reinforcer on responding in a free-operant task appear to be more complex than the predicted relationship suggests.

Harzem and Harzem (1981) suggested that local rather than overall response rates would more accurately reflect the relationship with reinforcer magnitude implied by a response-strength conception. Local response rates refer to response rates calculated by excluding the latency to first lever press following the termination of the reinforcer. Previous research has shown that local response rates either did not vary systematically (Kliner et al., 1988; Lowe et al., 1974; Powell, 1969; Priddle-Higson et al., 1976; Staddon, 1970) or increased with reinforcer magnitude (Harzem et al., 1978; Lowe et al., 1974; Reed & Wright, 1988). In sum, despite the fact that interpretation of the effects of reinforcer magnitude on responding is complicated by various issues, the assumption that reinforcer magnitude and response rates should vary directly still prevails.

Investigations of the relationship between reinforcer magnitude and free-operant responding with nonappetitive forms of reinforcement are less prevalent, and it remains open to question whether the relation implied by the response-strength conception

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would be observed with a nonappetitive form of reinforcement such as running. Specifically, if the duration of the opportunity to engage in nonappetitive behavior is a proxy for reinforcer magnitude, then, from the response-strength conception, as the duration of the opportunity to run increases, the rate of instrumental responding for that opportunity should increase.

Premack, Schaeffer, and Hundt (1964) conducted a systematic investigation of the effects of changes in the duration of the opportunity to run on rats licking a drinkometer on a fixed-ratio (FR) 10 schedule of reinforcement for the opportunity to run. Reinforcer durations varied from 2 to 20 s. Session duration was held constant at 20 min. As the duration of the reinforcer period increased, the number of quarter-turns of the wheel per session increased while the number of licks per session decreased. Because session time was held constant, however, a straightforward interpretation is that subjects ran more when given more time to run and licked less when less time was available to lick. The analysis also showed that the number of licks per reinforcer on the FR 10 schedule did not vary with reinforcer duration. Finally, the pause between the offset of running and the onset of the next burst of licking increased with reinforcer duration. Although response rates, in terms of licks per unit of time spent licking, were not calculated, the increase in the latency to lick following the termination of the running period suggests that overall response rates, which included the postreinforcement pause, decreased as reinforcer duration increased. This inverse relationship between overall response rates and reinforcer duration seems, on the surface, to be inconsistent with what one might expect based on the response-strength conception, but would be consistent with Premack et al.'s (1964) prediction that "increasing the CT [reinforcer duration] will allow the reinforcing response to habituate increasingly, and should therefore reduce the instrumental output" (p. 91).

More recently, Iversen (1993) exposed 2 rats to fixed-interval (FI) 6-min schedules for the opportunity to run for 5 and 9 s; a 3rd rat was exposed to reinforcer durations of 5, 9, and 15 s. Lever-pressing rates did not vary "appreciably or consistently" (p. 230) across

this range of reinforcer durations. Despite the lack of effect on lever-pressing rates, Iversen noted that running rate tended to increase as reinforcer duration decreased.

The purpose of the present study was to investigate the effect of reinforcer duration on running and on responding for the opportunity to run. Of particular interest was how the reinforcing value of running as indexed by rates of responding reinforced by the opportunity to run varies with the duration of that opportunity. Because Iversen's (1993) results showed no effect of reinforcer durations in the range of 5 to 15 s, durations ranging from 30 to 120 s were used here.

The schedule of wheel-running reinforcement was a tandem FR 1 variable-interval (VI) 30-s schedule under which the VI interval did not start timing until a single lever press was made. The first lever press after the programmed interval had elapsed caused the lever to retract and the brake on the wheel to release. The wheel turned freely for the duration of the reinforcer interval; then the brake was engaged, and the lever was extended.

Belke and Heyman (1994) introduced this response-initiated VI schedule based on the observation that long latencies to lever press, ranging on average from 20 to 40 s, persisted through the training phase despite the use of schedules of reinforcement that typically generate high response rates. They also observed that at the termination of the reinforcement period, animals would run up the sides of the wheel before returning to the area of the lever. The FR 1 component prevented these long latencies from decreasing response rates on VI schedules with short average intervals (i.e., VI 5 s).

METHOD

Subjects

Twelve male Wistar rats were obtained from Charles River. The rats were approximately 6 months old at the start of the experiment and had previous experience in an investigation that compared variable to fixed reinforcer duration of the opportunity to run as a reinforcer for lever pressing. They were housed individually in standard plastic cages (48 cm by 27 cm by 15 cm) in a holding room

on a 12:12 hr light/dark cycle (lights on from 8:00 a.m. to 8:00 p.m.). Immediately after each daily experimental session, the rats were weighed and were fed a measured amount of food to maintain them at a body weight that was 80% of an initial free-feeding weight that had been determined when the subjects were approximately 2 months old. The 80% body weights ranged from 280 to 304 g. Distilled water was available *ad lib* in the home cage.

Apparatus

Subjects were tested in standard activity wheels (two Wahmann Co. and two Med Associates ENV-041) with diameters of 35.5 cm. Wheel revolutions were recorded by a micro-switch attached to the wheel frame. A retractable lever (Med Associates ENV-112) was mounted at the opening of each wheel, and a solenoid-operated brake was attached to the base of each wheel. Each lever extended 1.8 cm into the chamber of the wheel through an opening (7 cm by 9 cm) located in the center at the base of the wheel frame. The force required to close the lever microswitches ranged from 18 to 27 g. Mounted on the side of the wheel frame were 24-V DC lights that served to illuminate the interior of the wheel. Wheels were located in sound-attenuating shells with fans to provide ventilation and masking noise. Control of experimental events and the recording of data were handled by Borland's Turbo Pascal programs on IBM® PC computers interfaced to the wheels through the parallel port. Each computer was located above the shell that contained the wheels.

Procedure

Each subject initially was given free access to the same running wheel for 30 min each day, and the number of wheel revolutions was recorded. During this phase, in addition to running, lever pressing was shaped in a standard operant conditioning chamber. Each lever press produced 0.1 ml of a 10% sucrose solution. When subjects reliably pressed the lever, the schedule of reinforcement was shifted from an FR 1 schedule to a series of variable-ratio (VR) schedules (i.e., VR 3, VR 5, VR 7, and VR 10). Each VR schedule was in effect for approximately three sessions; each session ended when 50 sucrose reinforcers had been obtained.

Throughout the period of lever training, subjects ran in the wheels for 30 min before lever-training sessions were conducted. When the rate of lever pressing for sucrose solution appeared to be stable, these sessions were discontinued. Instead, the retractable lever in each wheel chamber was extended during the wheel-running sessions, and the opportunity to run for 60 s was contingent upon a single lever press. A session then consisted of 30 opportunities to run. The schedule of reinforcement was changed in the following sequence: FR 1, VR 3, VR 5, and VR 9. Subjects remained on each schedule for three to five sessions before advancing to the next schedule. During this training phase, a rat was dropped from the study because 30 opportunities to run were not produced by the rat in less than 2 hr. Next, the schedule was shifted to VR 15, and the number of opportunities to run was decreased to 20 due to time constraints. Following the last day on the VR 15 schedule, it was changed to the tandem FR 1 VI 30-s schedule of running reinforcement. The VI 30-s schedule was comprised of 20 intervals that approximated an exponential distribution (Fleshler & Hoffman, 1962) and ranged from 1 to 120 s. Across sessions, the order of intervals was randomized.

All subjects participated in a manipulation in which the reinforcer duration was shifted from a fixed value to a variable value with the same mean (data not presented) before a return to the 60-s reinforcer duration for the present experiment. There were 40 sessions with the 60-s reinforcer duration for all rats. Then reinforcer duration was changed to 30 s for 6 subjects (R3, R4, R6, R7, R8, and R9) and 120 s for the remaining 5 subjects (R1, R2, R5, R10, and R11). Subjects were exposed to these reinforcer durations for 25 sessions. Then subjects that had been exposed to the 120-s duration were changed to a 30-s duration, and subjects that had been exposed to the 30-s duration were changed to a 120-s duration. Sessions were conducted between 9:00 a.m. and 2:00 p.m., 7 days a week.

Lever presses, wheel revolutions, and latency to the first lever press following termination of the reinforcement period were recorded for each reinforcer and collectively for the entire session. Wheel-running rates were calculated as the total number of revolutions divided by the total time during which

Table 1

Mean number of revolutions per minute over the last 3 days of the 30-min free-wheel condition and the last 3 days of the 3 to 5 days that the FR 1, VR 3, VR 5, and VR 9 training conditions were in effect for each rat. The data represent the wheel-running rates expressed as revolutions per minute of opportunity to run that occurred during 30 continuous minutes of opportunity to run in the 30-min condition and 30 1-min opportunities to run in the remaining conditions, where the opportunity to run was contingent upon lever pressing.

Condi- tion	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	M
30 min	24.2	19.8	8.5	9.3	21.5	20.1	28.1	14.0	31.5	9.8	15.5	18.4
FR 1	20.7	23.7	11.1	12.7	26.6	19.2	30.4	15.8	26.6	20.3	21.2	20.8
VR 3	27.9	28.6	18.1	12.4	25.6	26.5	33.5	20.5	26.2	24.7	28.9	24.8
VR 5	31.7	33.4	20.3	13.7	29.4	30.5	36.4	22.1	25.3	28.1	29.2	27.3
VR 9	31.6	34.8	24.0	16.9	35.2	30.1	36.9	31.0	28.8	28.8	32.8	30.1

running could occur, expressed as revolutions per minute. Mean latency to the first postreinforcement lever press was calculated as cumulative latencies per session divided by the number of reinforcers. Local lever-pressing rates were calculated as the total number of responses per session divided by the time available for lever pressing, not inclusive of latencies to the first postreinforcement response.

RESULTS

Table 1 presents the mean wheel-running rates obtained over the last 3 days of the 30-min free-wheel condition and the last 3 days of the 3 to 5 days for the FR 1, VR 3, VR 5, and VR 9 conditions for the 11 rats that progressed through training. Mean rates of running for the 30-min free-wheel, FR 1, VR 3, VR 5, and VR 9 conditions were 18.4, 20.8, 24.8, 27.3, and 30.1 revolutions per minute, respectively. These data show that during training the rate of wheel running increased when the opportunity to run was made contingent upon lever pressing. The relevance of these data will be addressed in the Discussion.

To examine the effect of changes in reinforcer duration, data from the last five sessions on each duration were analyzed. Figure 1 shows that as the duration of the opportunity to run increased, the mean rate of running usually decreased. For all animals, rates of running decreased with increases in reinforcer duration. For the group, mean rates of running for the 30-, 60-, and 120-s reinforcer-duration conditions were 40.7, 35.0, and 30.2 revolutions per minute, respectively. A repeated measures ANOVA revealed a signifi-

cant effect of reinforcer duration, $F(2, 20) = 122$, $p < .0001$. Post-hoc Dunnett t -test comparisons showed that the differences between the 30- and 60-s conditions, $t(20) = 8.5$, $p < .01$, the 30- and 120-s conditions, $t(20) = 15.6$, $p < .01$, and the 60- and 120-s conditions, $t(20) = 7.1$, $p < .01$, were significant.

Figure 2 shows that mean latency to the first postreinforcement lever press increased as a function of reinforcer duration for 9 of 11 animals. Rat 4's latency to press showed little variation across the arranged reinforcer durations, whereas Rat 8's latency showed little variation between the 60-s and 120-s reinforcer durations. For the group, mean latencies for the reinforcer durations of 30, 60, and 120 s were 22.5, 34.3, and 58.6 s, respectively. A repeated measures ANOVA showed a significant effect of reinforcer duration, $F(2, 20) = 27.0$, $p < .0001$. Post-hoc Dunnett t -test comparisons showed that differences in latency between the 30- and 120-s, $t(20) = 7.2$, $p < .01$, and the 60- and 120-s, $t(20) = 4.8$, $p < .01$, reinforcer durations were significant. An additional analysis of the distributions of latencies over the last five sessions revealed that median latencies changed systematically with reinforcer duration. Average median latencies for the 30-, 60-, and 120-s conditions were 19.8, 28.8, and 46.4 s, respectively. This analysis showed that the changes observed in the mean values were not due simply to extreme values.

Figure 3 shows mean local rates of lever pressing as a function of reinforcer duration. Although group-mean local lever-pressing rates decreased as reinforcer duration increased, inspection of the data for individual

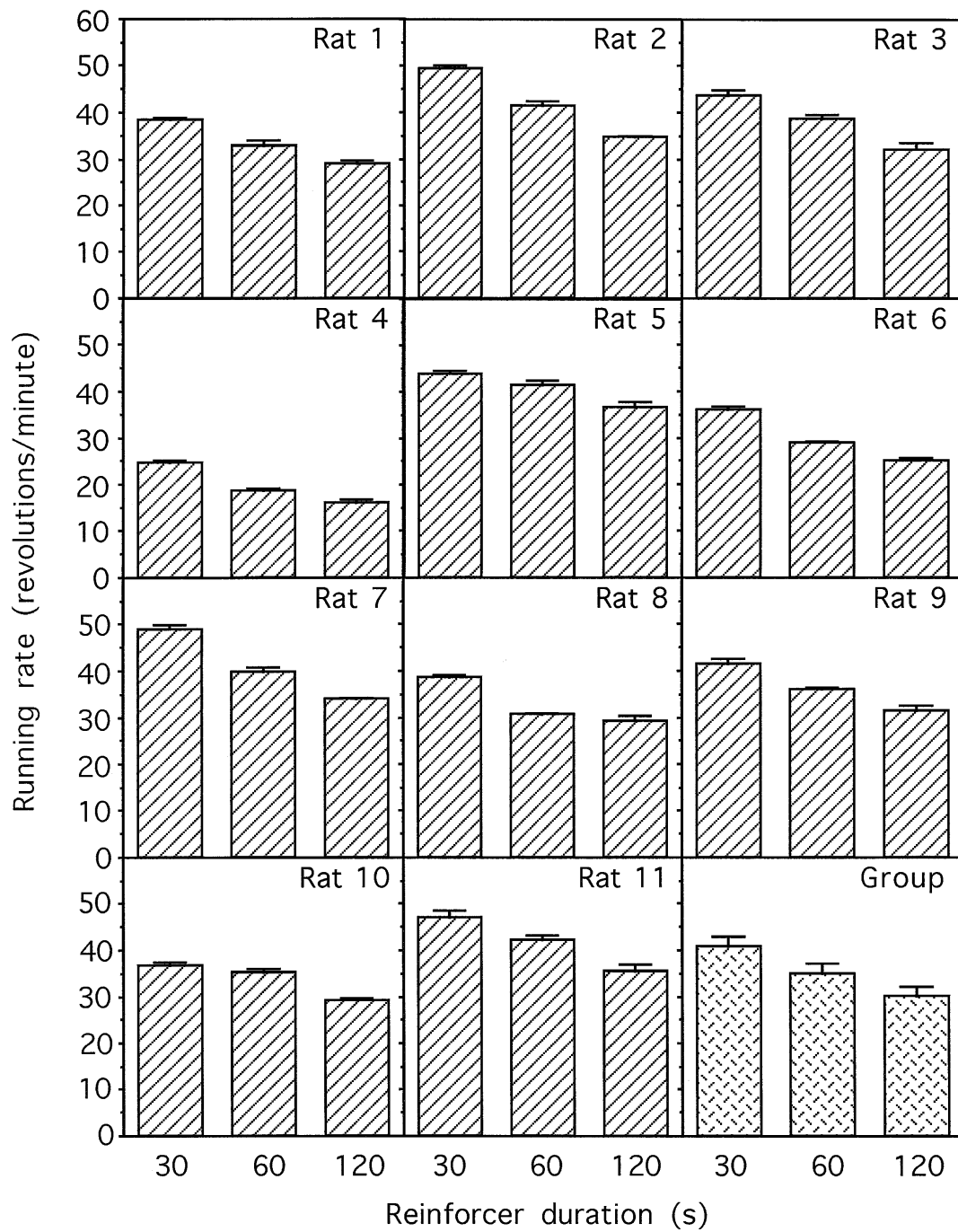


Fig. 1. Mean wheel-running rate for each rat and for the group as a function of reinforcer duration. Mean values and standard errors were calculated from the last five sessions under each reinforcer duration.

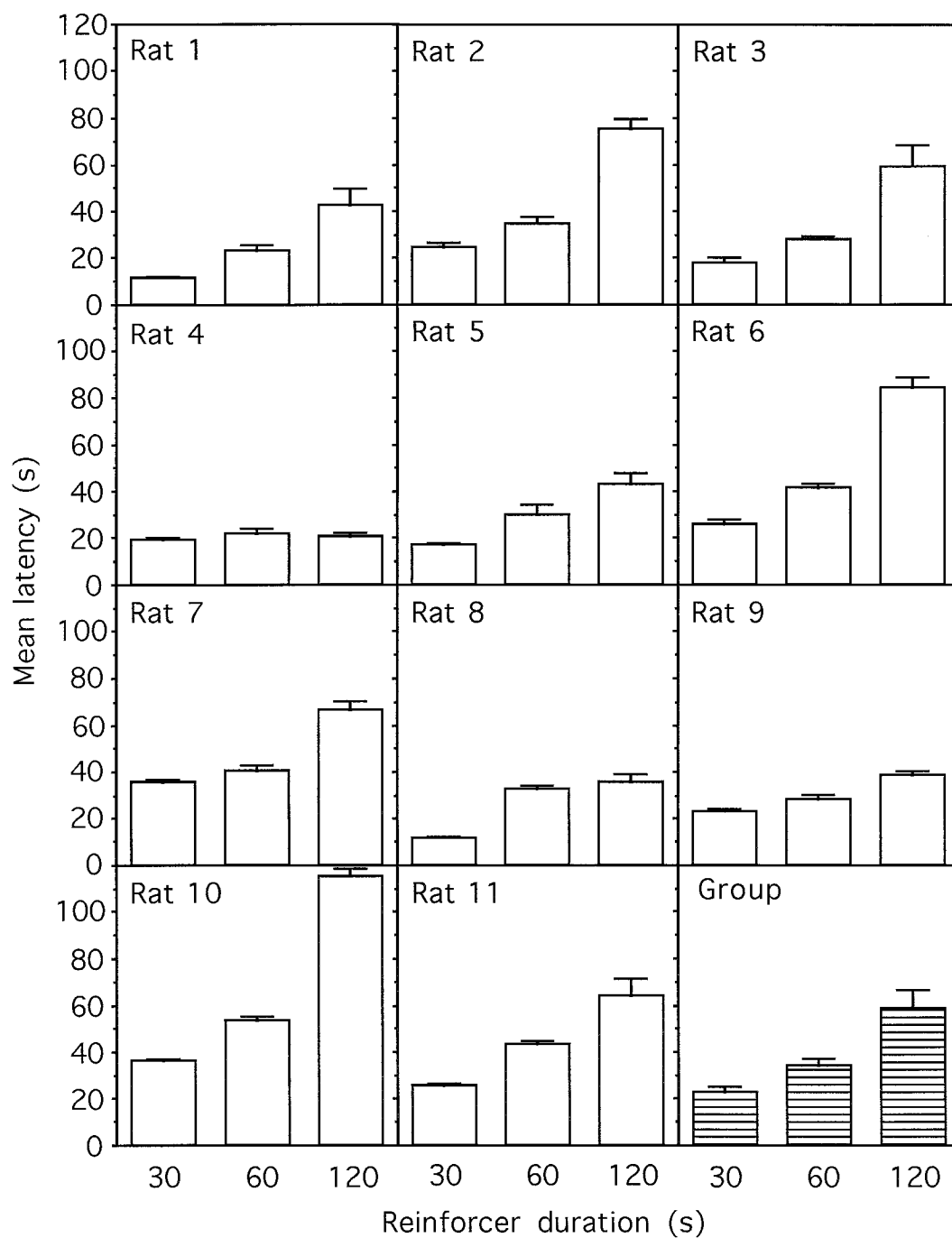


Fig. 2. Mean latency to the first lever press following reinforcement for the FR 1 component of the tandem FR 1 VI 30-s schedules for individual rats and for the group as a function of reinforcer duration. Means and standard errors were calculated from the last five sessions under each reinforcer duration.

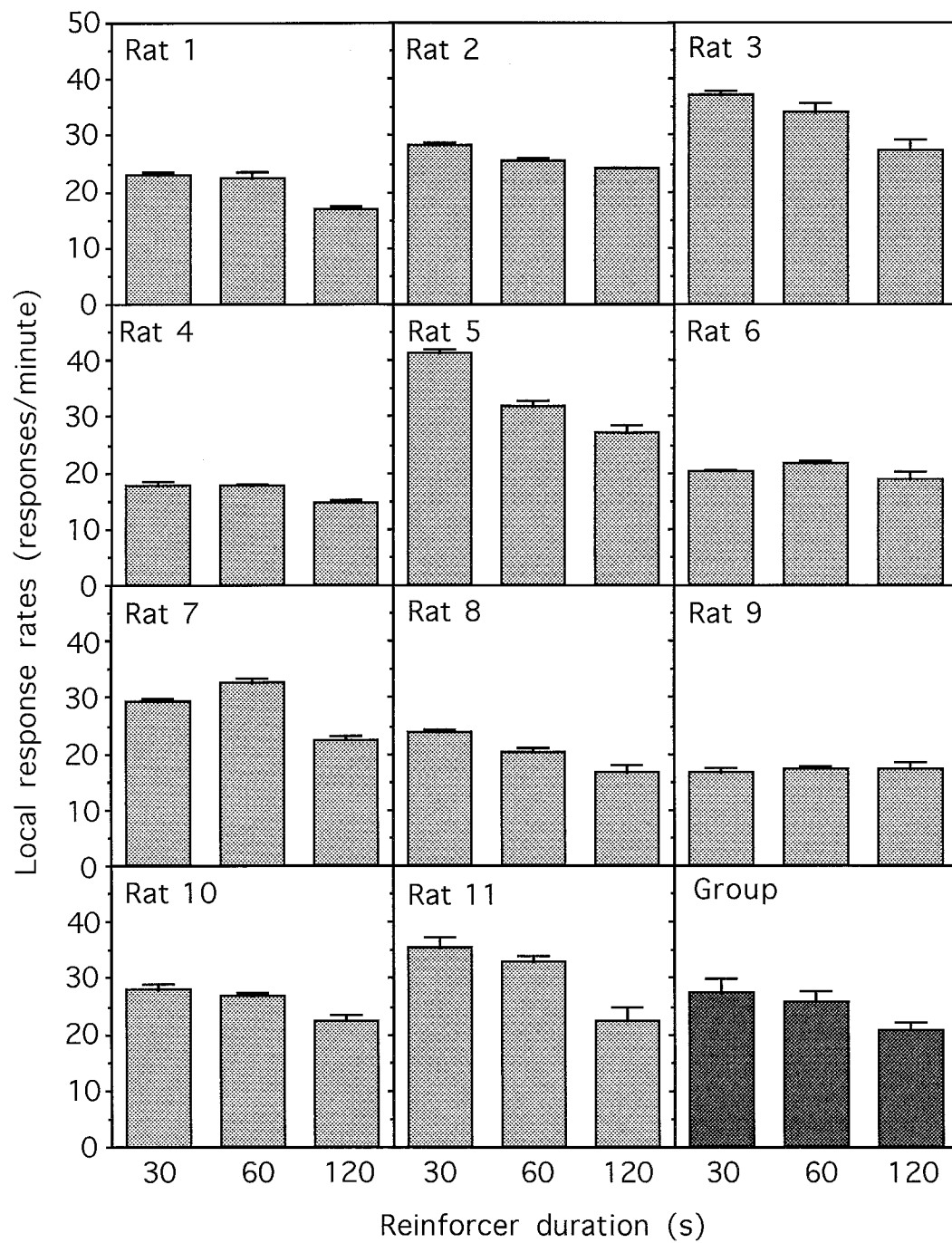


Fig. 3. Mean local lever-pressing rate for the VI 30-s component of the tandem FR 1 VI 30-s schedules for each rat and for the group as a function of reinforcer duration. Means and standard errors were calculated from the last five sessions under each reinforcer duration.

animals revealed that only 5 of the 11 rats showed this pattern of differences. Rats 6 and 7 had higher local rates on the 60-s duration than on the 30-s duration. The local response rate for Rat 9 did not differ systematically among durations, whereas those for Rats 1, 4, and 10 differed little between the 30- and 60-s durations. For the group, mean local lever-pressing rates for the 30-, 60-, and 120-s conditions were 27.3, 25.7, and 20.8 responses per minute, respectively. Statistical analysis revealed a significant effect of reinforcer duration, $F(2, 20) = 17.4$, $p < .0001$, and post-hoc comparisons showed that the differences between the 30- and 120-s conditions, $t(20) = 5.7$, $p < .01$, and the 60- and 120-s conditions $t(20) = 4.3$, $p < .01$, attained significance.

Within-session patterns of rates of running, latencies to the first postreinforcement lever press, and local lever-pressing rates for the 30-, 60-, and 120-s reinforcer durations are depicted in Figures 4, 5, 6, respectively. Within-session patterns were analyzed for linear trend.

Figure 4 shows that, in general, the rate of running tended to increase throughout the session. With the exception of Rat 4, running rates in either or both the 30- and 60-s durations increased from the first to the last reinforcer for each rat. On average, running rates in the 60- and 120-s conditions increased by 9.9 and 10.2 revolutions per minute, respectively, from the first to the last four reinforcers. For the 30-s condition, the rates of running for Rats 5, 6, 7, 8, 10, and 11 increased throughout the session and on average, running rates increased by 3.6 revolutions per minute. Linear trend analyses revealed significant trends for the 60-s, $F(1, 10) = 28.0$, $p < .0001$, and the 120-s, $F(1, 10) = 27.4$, $p < .0001$, reinforcer durations, but not for the 30-s duration, $F(1, 10) = 2.99$, $p < .10$.

Figure 5 shows that no systematic within-session patterns were apparent in the latencies to the first postreinforcement lever press. Trend analyses indicated no significant linear trends for any duration.

Figure 6 shows that for the 30- and 60-s durations, but not for the 120-s duration, there was a tendency for local lever-pressing rates to increase from the first to the last reinforcer. Increases are evident for Rats 1, 2, 3, 6, 9,

and 11 under the 30-s condition and for Rats 1, 3, 4, 5, 6, 7, 9, and 10 under the 60-s condition. In contrast, for the 120-s conditions, increases were apparent for Rats 5 and 11. Trend analyses revealed significant linear trends for the 30-s, $F(1, 10) = 8.27$, $p < .05$, and 60-s, $F(1, 10) = 10.43$, $p < .01$, reinforcer durations. For these conditions, mean local response rates increased by 3.83 and 6.48 responses per minute between the first and last groups of reinforcers, respectively.

Table 2 presents the correlations between revolutions that occurred during a reinforcement period and the duration of the immediately following latency to lever press for each animal in each condition. For this analysis, the first latency to press the lever in a session and revolutions in the last reinforcement period in a session were removed for each of the last five sessions in each condition. Inspection of this table reveals no systematic relationship between the number of revolutions run and the duration of the immediately following latency to lever press under any reinforcer duration. Of 33 correlations calculated, 22 were not significant; of the significant correlations, six were positive and five were negative.

Finally, for the 30-, 60-, and 120-s reinforcer durations, mean session durations were 28.36, 42.56, and 71.24 min, respectively. Of these durations, total cumulative time provided for running constituted 10, 20, and 40 min, respectively. Mean cumulative latencies to respond were 7.5, 11.44, and 19.54 min, respectively. The minimum time required to complete the schedule requirement for all 20 reinforcement intervals constituted 10 min of the session in each condition, and mean time in excess of this minimum for the 30-, 60-, and 120-s durations was 0.87, 1.11, and 1.70 min, respectively.

DISCUSSION

As reinforcer duration increased, rate of running and local lever-pressing rate decreased while the latency to the first postreinforcement lever press increased. Within-session analyses revealed that subjects usually ran at a high rate throughout the session at the shortest (30-s) reinforcer duration. At longer (60-s and 120-s) durations, rate of running increased throughout the session toward

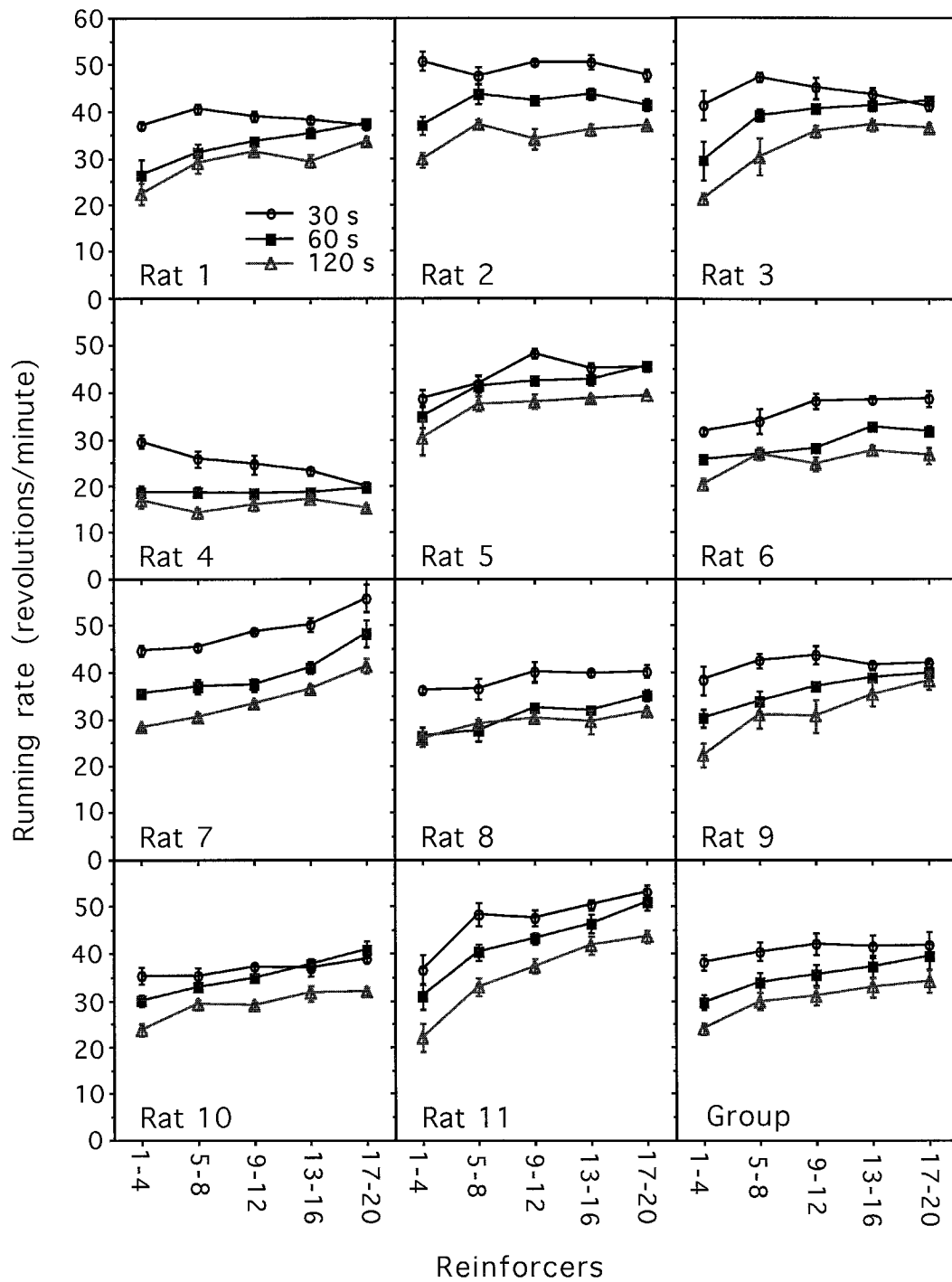


Fig. 4. Within-session changes in wheel-running rate for each reinforcer duration for individual rats and for the group. Data points are means and standard errors calculated for successive groupings of four reinforcers over the last five sessions under each reinforcer duration.

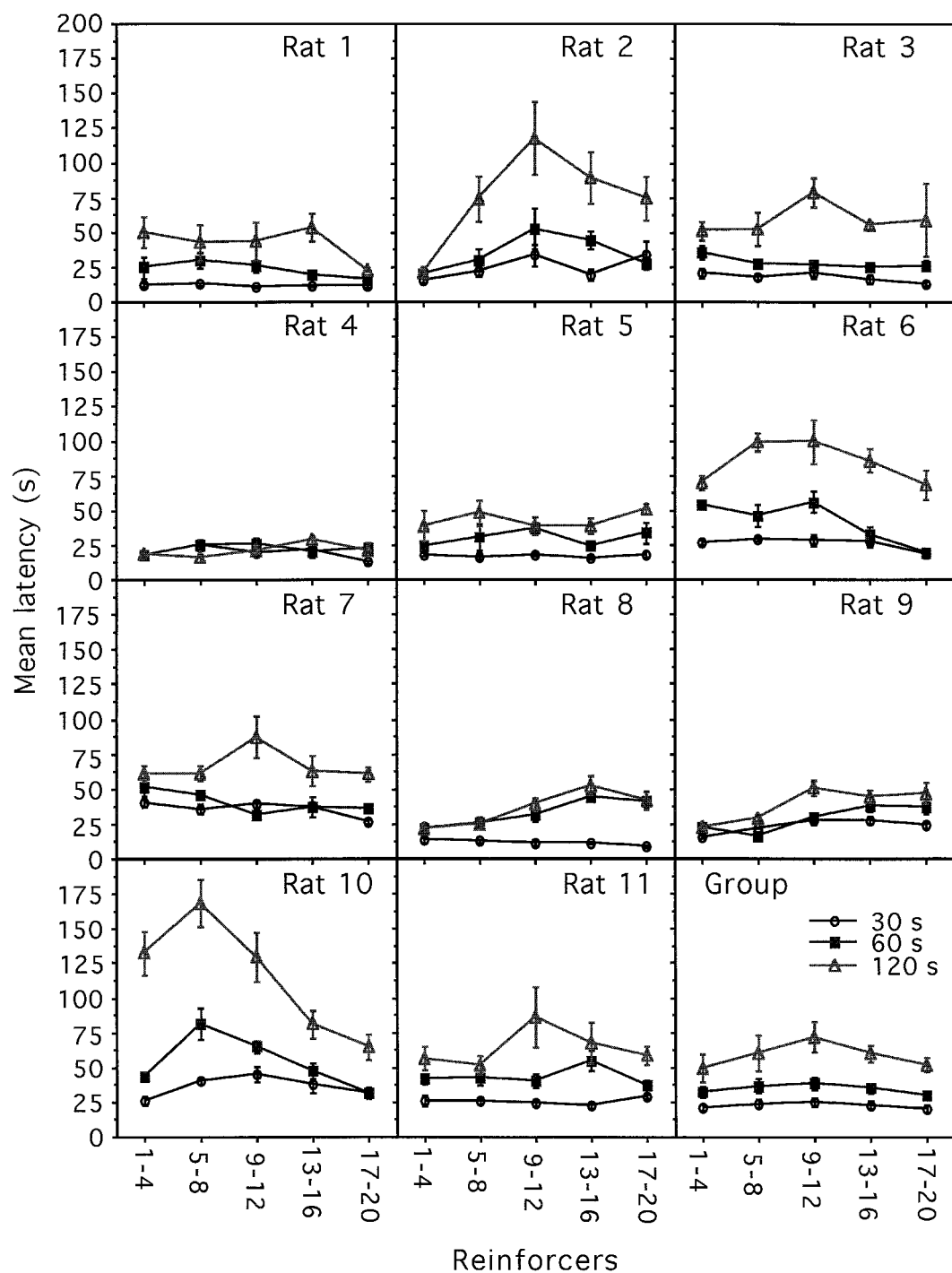


Fig. 5. Within-session changes in latency to the first lever press following reinforcement for the FR 1 component of the tandem FR 1 VI 30-s schedules for each reinforcer duration for individual rats and for the group. Data points are means and standard errors calculated for successive groupings of four reinforcers over the last five sessions under each reinforcer duration.

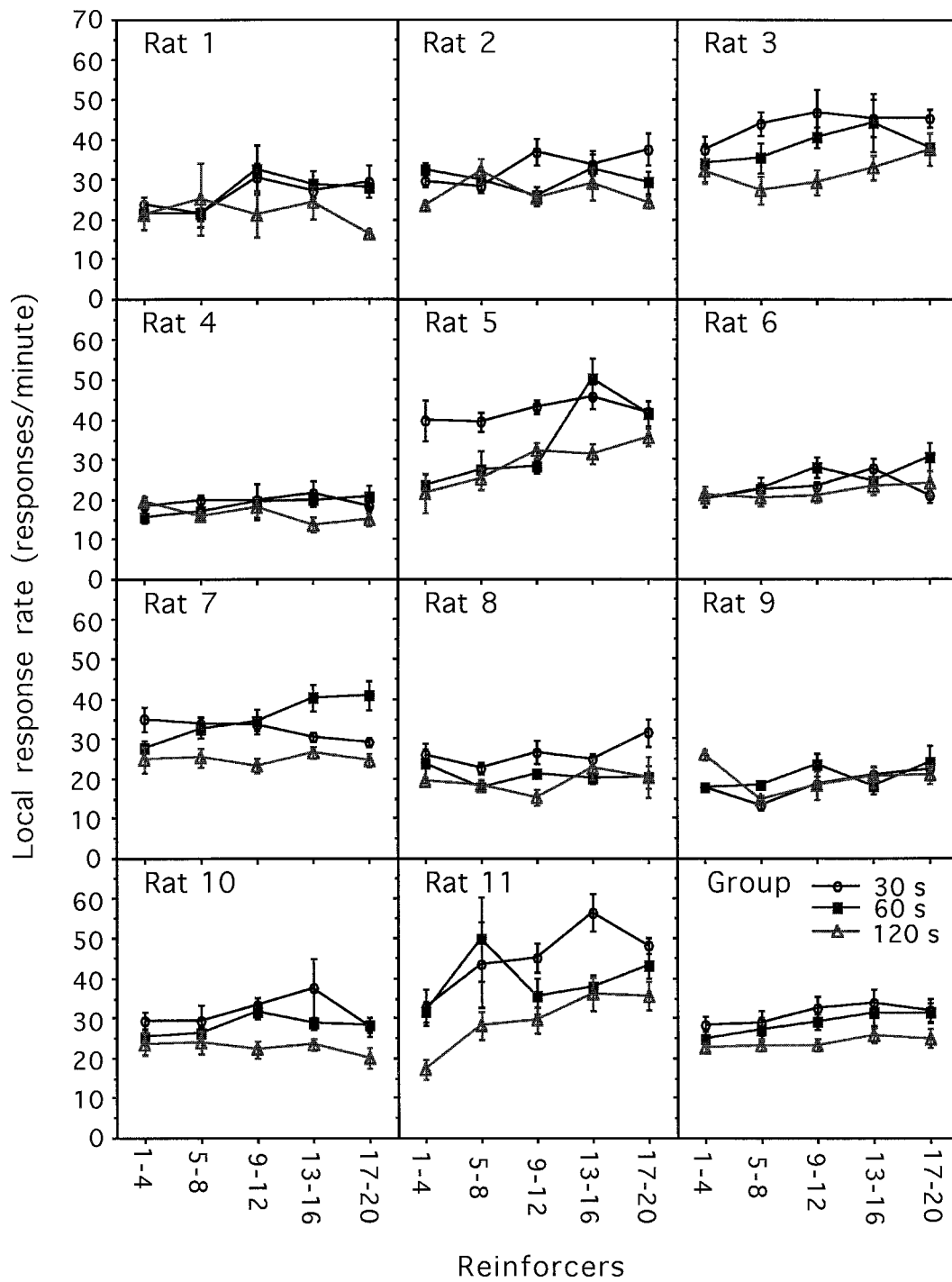


Fig. 6. Within-session changes in local lever-pressing rate for the VI 30-s component of the tandem FR 1 VI 30-s schedules for each reinforcer duration for individual rats and for the group. Data points are means and standard errors calculated for successive groupings of four reinforcers over the last five sessions under each reinforcer duration.

Table 2

Correlations (Pearson r values) between wheel revolutions in a reinforcement period and the duration of the immediately following latency to the first lever press calculated from the last five sessions of each reinforcer-duration condition for each rat. Associated probabilities are shown in parentheses.

Rat	Reinforcer duration		
	30 s	60 s	120 s
R1	.03 (.78)	-.52 (.00)	-.22 (.03)
R2	-.01 (.96)	.13 (.21)	-.07 (.52)
R3	.05 (.64)	-.13 (.21)	.03 (.81)
R4	.22 (.03)	-.02 (.85)	.12 (.27)
R5	.06 (.60)	-.23 (.03)	.07 (.53)
R6	.02 (.84)	-.19 (.06)	-.01 (.96)
R7	.25 (.02)	.12 (.27)	-.02 (.84)
R8	.12 (.25)	.26 (.01)	.05 (.67)
R9	.27 (.01)	.34 (.00)	.25 (.02)
R10	-.07 (.48)	-.29 (.00)	-.35 (.00)
R11	.15 (.14)	.02 (.87)	-.03 (.81)

the level of running that occurred at the short duration. No consistent within-session changes were apparent for mean latency. Local lever-pressing rate tended to increase across the session in the 30- and 60-s durations for some, but not all, animals.

In general, these results show that increases in duration of the opportunity to run as a reinforcing consequence for operant behavior produce changes in operant behavior that are similar to those that have been observed when durations of the opportunity to eat, concentration of sucrose solution, or size of food pellet were increased. Specifically, the increase in duration of the postreinforcement latency with increases in reinforcer magnitude has been observed consistently over many studies using appetitive reinforcement (Harzem et al., 1978; Lowe et al., 1974; Perone & Courtney, 1992; Priddle-Higson et al., 1976; Reed & Wright, 1988; Staddon, 1970) and has been previously observed by Premack et al. (1964) for running as a reinforcer.

Perone and Courtney's (1992) research suggests that this direct relationship between reinforcer duration and postreinforcement latency reflects the dominance of an unconditioned inhibitory aftereffect of the previous reinforcer in a context in which control by an excitatory effect associated with stimuli correlated with the upcoming reinforcer is weak. In the present study, the stimuli correlated

with the upcoming reinforcer were the onset of the brake terminating the reinforcement period and the extension of the retractable lever. These stimuli did not vary across reinforcer durations. As a consequence, according to Perone and Courtney (1992), potential differential excitatory effects related to stimuli associated with the different magnitudes were not expressed.

It is important to note that unlike most previous studies, the present study used a tandem FR 1 VI 30-s schedule rather than a simple schedule; this may limit the generality of the findings. Previous research suggests that the effect of response-initiated interval reinforcement schedules is to lengthen latencies to respond; however, this effect appears to be independent of the effect of reinforcer magnitude on latencies to respond. Lowe et al. (1974) found that postreinforcement pauses on a tandem FR 1 FI 60-s schedule were approximately twice as long as those observed for an FI 60-s schedule of reinforcement. Despite this, postreinforcement pauses were still observed to increase with reinforcer magnitude.

The second finding of the present study was that as reinforcer duration increased, local lever-pressing rates decreased. Although this effect was not as systematic as the effect on postreinforcement latency, it nevertheless poses a challenge for a response-strength interpretation of reinforcement (de Villiers & Herrnstein, 1976; Herrnstein, 1970). This interpretation implies a direct rather than an inverse relationship between local response rates and magnitude of reinforcement (Harzem & Harzem, 1981). From this perspective, the results of the present experiment suggest either that the value of an opportunity to run as a reinforcing consequence was greater when the duration of that opportunity was shorter (in other words, that less was more) or that other factors acted to mask a direct relation.

Interpretation of the observed changes in local rates of lever pressing, together with changes in the rates of running and postreinforcement latency, requires consideration of a number of alternative processes such as satiation, fatigue, and response deprivation. Satiation refers to a decline in the effectiveness of a reinforcer to maintain responding as a function of consumption of the reinforc-

ing consequence. In other words, as reinforcer magnitude increases, consumption of the reinforcer and responding for reinforcement may decline due to satiation (e.g., Conrad & Sidman, 1956; Guttman, 1953).

In the present study, the decline in running rate and in local lever-pressing rate, in combination with increases in postreinforcement latency, could be attributed to the effects of satiation for running. However, the within-session data do not suggest that satiation for running occurred. On the contrary, for the longer reinforcer durations that would presumably produce greater satiation, rates of running increased throughout the session. Nor did latencies to the first postreinforcement lever press systematically increase throughout the session, as would be expected as a function of satiation.

Fatigue is another factor that could produce a decline in running and response rates as well as an increase in latency to respond as reinforcer duration increased. As duration increased, running rates decreased; however, revolutions per opportunity to run increased. Mean revolutions per opportunity to run in the 30-, 60-, and 120-s conditions were 20.4, 35.0, and 60.4 revolutions, respectively. Thus, as reinforcer duration increased, animals ran more and may have become fatigued. Increased fatigue could then produce an increase in the postreinforcement latency to respond and an increase in interresponse intervals.

As with satiation, the within-session data do not support fatigue as an explanation for the results. First, running rates would be expected to decline throughout the session as fatigue increased, but they did not. Latencies would be expected to be higher at the end of the session than at the beginning, and response rates would be expected to decrease rather than increase. Clearly, this was not the case. Furthermore, if the conditions produced different general levels of fatigue, one might expect that rates of running would be most similar at the beginning of the session, when all subjects were equally rested, and to diverge as subjects in the longer reinforcer duration conditions became progressively more fatigued. In fact, running rates among the three conditions were generally more disparate at the beginning of the session and less disparate at the end of the session. Thus,

although changes in overall running rates, lever-pressing rates, and latency to respond were consistent with an explanation of fatigue, within-session data did not substantiate this explanation.

Of course, the foregoing account is based on the assumption that fatigue varies with total number of revolutions run rather than rate of running. An alternative assumption would be that fatigue varies with rate of running. Under this assumption, the faster one runs, the greater the fatigue. This assumption would predict lower response rates and longer latencies for the shorter reinforcer duration, which produced the highest running rate. The data show, however, that response rates were higher and latencies were shorter at the shorter reinforcer duration.

It is important to note that the considerations of satiation and fatigue just offered are based on an assumption of a cumulative effect throughout the session. Alternatively, the effects of reinforcer duration could be due to a local satiation or fatigue effect that does not cumulate. After running, the animal would be momentarily satiated for running or momentarily fatigued, and the probability of pressing for the opportunity to run would be lowest following the termination of a running bout. With longer durations, the momentary satiation or fatigue would be greater. This account suggests that there might be a positive correlation between running in a reinforcement period and the latency to respond following the termination of that reinforcement period. In particular, the latency to respond following the termination of a reinforcement period in which more running had occurred would be longer than the latency following the same period in which less running had occurred. Contrary to this prediction, however, no systematic relationship was apparent between the number of revolutions run and the duration of the following latency to lever press within reinforcer durations. The lack of a relationship within a duration challenges the view that local effects might explain the differences between durations. (It should be noted, however, that the range of variability is smaller within than between conditions, which could result in low within-duration correlations even if local factors were influential in generating the between-duration effects.)

Finally, response deprivation (Allison,

1993; Timberlake & Allison, 1974) provides an alternative to the response-strength conception for interpreting the changes in running and responding for the opportunity to run as the duration of that opportunity increased. According to this approach, without any constraints, rats run in wheels and press levers at baseline rates that define a paired baseline. A schedule constraint that makes the opportunity to run contingent upon lever pressing deprives the individual of the contingent behavior. The behavioral response to this deprivation will be a facilitation of the instrumental responding (i.e., lever pressing above baseline rate) and a suppression of the contingent behavior (i.e., running below baseline levels) (Allison, 1993).

In the present experiment, increases in reinforcer duration decreased the constraint placed on the contingent behavior. Under less constrained conditions, running should more closely approximate unconstrained levels. In other words, as the restriction on the behavior of running decreased, motivation to respond for the opportunity to run should have decreased, producing a concomitant decline in responding reinforced by the opportunity to run and an increase in latency to respond. Thus, a response-deprivation account appears to accommodate the inverse relationship between reinforcer duration and local lever-pressing rate as well as the direct relationship between duration and latency to respond.

Lucas (1981) demonstrated a similar effect of reinforcer duration on the response rates of pigeons responding on an FI schedule for food reinforcement in a closed economy. In his second experiment, Lucas showed that local response rates (i.e., key pecks divided by the total cumulative time spent responding) were an inverse function of the duration of access to food. Furthermore, Lucas also suggested that rate of eating increased as reinforcer duration decreased, given that the pigeons maintained their body weights despite a decrease in daily access time to food. Thus, Lucas's results resemble the observed changes in local lever-pressing and running rates in the present study.

However, as was the case for satiation and fatigue, the within-session data bring the adequacy of a response-deprivation account into question. Within a session, deprivation

for running would be highest at the start of the session and should decline as the rats ran more and more into the session. Consequently, rates of lever pressing and running would be expected to decline throughout the session, yet they did not. In fact, running rates show the opposite pattern for the longer durations; they increased throughout the session. Data from the training phase also question the adequacy of a response-deprivation account. As is evident in Table 1, making the opportunity to run contingent upon lever pressing did not suppress the contingent behavior. On the contrary, the number of revolutions per unit time of opportunity to run increased rather than decreased as the schedule constraint changed from FR 1 to VR 9.

In sum, running and responding reinforced by the opportunity to run changed systematically with changes in the duration of opportunity to run. Changes in latency to respond were consistent with changes observed when the magnitude of appetitive forms of reinforcement have been varied and can be accounted for by unconditioned inhibitory aftereffects of reinforcement. Changes in local rates of lever pressing seemed to be inconsistent, however, with a response-strength interpretation of reinforcement. Nor were the changes in running, lever pressing, and latency to respond, when considered collectively, adequately explained by satiation, fatigue, or response deprivation. This failure to account for the observed changes, although it leaves the reader unsatisfied, underscores the need for further investigation of nonappetitive reinforcing consequences.

REFERENCES

- Allison, J. (1993). Response deprivation, reinforcement, and economics. *Journal of the Experimental Analysis of Behavior*, 60, 129-140.
- Belke, T. W., & Heyman, G. M. (1994). A matching law analysis of the reinforcing efficacy of wheel running in rats. *Animal Learning & Behavior*, 22, 267-274.
- Catania, A. C. (1963). Concurrent performances: A baseline for the study of reinforcement magnitude. *Journal of the Experimental Analysis of Behavior*, 6, 299-300.
- Conrad, D. G., & Sidman, M. (1956). Sucrose concentration as reinforcement for lever pressing by monkeys. *Psychological Reports*, 2, 381-384.
- de Villiers, P. A., & Herrnstein, R. J. (1976). Toward a law of response strength. *Psychological Bulletin*, 83, 1131-1153.
- Fleshler, M., & Hoffman, H. S. (1962). A progression for

- generating variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, 5, 529-530.
- Guttman, N. (1953). Operant conditioning, extinction, and periodic reinforcement in relation to concentration of sucrose used as a reinforcing agent. *Journal of Experimental Psychology*, 46, 213-224.
- Harzem, P., & Harzem, A. L. (1981). Discrimination, inhibition, and stimulus association of stimulus properties: A theoretical analysis of reinforcement. In P. Harzem & M. D. Zeiler (Eds.), *Advances in analysis of behavior: Vol. 2. Predictability, correlation, and contiguity* (pp. 81-124). Chichester, England: Wiley.
- Harzem, P., Lowe, C. F., & Priddle-Higson, P. J. (1978). Inhibiting function of reinforcement: Magnitude effects on variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, 30, 1-10.
- Herrnstein, R. J. (1970). On the law of effect. *Journal of the Experimental Analysis of Behavior*, 13, 243-266.
- Hutt, P. J. (1954). Rate of bar pressing as a function of quality and quantity of food reward. *Journal of Comparative and Physiological Psychology*, 47, 235-239.
- Iversen, I. H. (1993). Techniques for establishing schedules with wheel running as reinforcement in rats. *Journal of the Experimental Analysis of Behavior*, 60, 219-238.
- Jenkins, W. O., & Clayton, F. L. (1949). Rate of responding and amount of reinforcement. *Journal of Comparative and Physiological Psychology*, 42, 174-181.
- Keesey, R. E., & Kling, J. W. (1961). Amount of reinforcement and free-operant responding. *Journal of the Experimental Analysis of Behavior*, 4, 125-132.
- Kliner, D. J., Lemaire, G. A., & Meisch, R. A. (1988). Interactive effects of fixed-ratio size and number of food pellets per fixed ratio on rats' food reinforced behavior. *Psychological Record*, 38, 121-143.
- Lowe, C. F., Davey, G. C. L., & Harzem, P. (1974). Effects of reinforcement magnitude on interval and ratio schedules. *Journal of the Experimental Analysis of Behavior*, 22, 553-560.
- Lucas, G. A. (1981). Some effects of reinforcer availability on the pigeon's responding in 24-hour sessions. *Animal Learning & Behavior*, 9, 411-424.
- Meltzer, D., & Brahlek, J. A. (1968). Quantity of reinforcement and fixed-interval performance. *Psychonomic Science*, 12, 207-208.
- Meltzer, D., & Brahlek, J. A. (1970). Quantity of reinforcement and fixed-interval performance: Within-subjects effects. *Psychonomic Science*, 20, 30-31.
- Perone, M., & Courtney, K. (1992). Fixed-ratio pausing: Joint effects of past reinforcer magnitude and stimuli correlated with upcoming magnitude. *Journal of the Experimental Analysis of Behavior*, 57, 33-46.
- Powell, R. W. (1969). The effect of reinforcement magnitude upon responding under fixed-ratio schedules. *Journal of the Experimental Analysis of Behavior*, 12, 605-608.
- Premack, D., Schaeffer, R. W., & Hundt, A. (1964). Reinforcement of drinking by running: Effect of fixed ratio and reinforcement time. *Journal of the Experimental Analysis of Behavior*, 7, 91-96.
- Priddle-Higson, P. J., Lowe, C. F., & Harzem, P. (1976). Aftereffects of reinforcement on variable-ratio schedules. *Journal of the Experimental Analysis of Behavior*, 25, 347-354.
- Reed, P., & Wright, J. E. (1988). Effects of magnitude of food reinforcement on free operant response rates. *Journal of the Experimental Analysis of Behavior*, 49, 75-85.
- Staddon, J. E. R. (1970). Effect of reinforcement duration on fixed-interval responding. *Journal of the Experimental Analysis of Behavior*, 13, 9-11.
- Stebbins, W. C., Mead, P. B., & Martin, J. M. (1959). The relation of amount of reinforcement to performance under a fixed-interval schedule. *Journal of the Experimental Analysis of Behavior*, 2, 351-355.
- Timberlake, W., & Allison, J. (1974). Response deprivation: An empirical approach to instrumental performance. *Psychological Review*, 81, 146-164.

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